ASTRONOMICAL OBSERVATIONS BY MEANS OF HIGHLY SENSITIVE ELECTRONIC LIGHT AMPLIFICATION

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Several different systems have been devised and used for observing and recording the image or information produced by a telescope. Many investigators have employed a photomultiplier tube. Hunten (1953) made use of one in the study of the aurora. Gehrels (1959) used one in the study of the polarization of the light of the moon and planets. Other investigators have made use of the photoelectric cell with suitable amplification. Stebbins of the United States (1910) and Guthnick of Germany (1913) were pioneers in developing this instrument for the study of variable stars. With a spectroscopic analysis and using a lead selenide cell, Sinton (1957, 1959) found evidence of vegetation on Mars. Oke (1957) has developed a new photoelectric spectrometer that measures light variation in 21 different wavelengths between 3400 and 5200 Angstroms. Hall (1958) and his coworkers (1959) have intensified the faint photographic image by various means. Electron image-converters have been developed in both the U.S.S.R. and the United States. Hiltner and his associates (1955) have worked in this field in the United States. An electronic camera that has proven very satisfactory has been developed by Lallemand of the Paris Observatory (1936, 1958). The use of closed circuit television arrangements has been investigated by McGee (1955) and Felgett (1955). Different fields of investigation require different systems. This paper will treat only electronic devices that do not employ mechanical scanning. Improvements that make possible very sensitive closed circuit television systems for astronomical observations will be described. The work was performed under a research program sponsored by the United States Air Force under the guidance of Gebel, who is one of the authors. The astronomical observations were made at Wittenberg University in cooperation with Wylie, who is another one of the authors.

The exposure time needed for astronomical observations may be decreased in a simple way by the use of the image-converter tube. The image is focused on the photocathode of the image-converter and the emitted electrons constitute an electron image. Intensification is accomplished by giving these electrons a high level of energy by accelerating them in an electric field. The intensified visible image, which can be observed or photographed, is produced by the impact of these electrons on a phosphor screen. If one only wants a photographic record, the phosphor screen may be replaced by an electron-sensitive plate. This is the electronic camera of Lallemand (1936, 1958). Recent models of this camera have several photographic plates on a revolving drum that is inside the vacuum of the tube, but which can be manipulated from outside the vacuum. The exposed plates can only be recovered by opening the tube. A photographic speed, that is better than one hundred times as great as that obtainable with photographic plates ordinarily used, is achieved by this system, and it has a resolution that is better than two hundred lines per millimeter.

The phosphor screen and glass on which the screen is placed may be replaced by a very thin metal foil, known as a Lenard window. The Lenard window permits electrons to pass out of the vacuum of the tube. The electron-sensitive plate is pressed directly against the Lenard window, and therefore a large number of plates may be exposed without breaking the tube (Pauli, 1910; Coolidge, 1926; Vollrath, 1931; Von Boris, 1932). The results obtained with the Lenard window are not as good, so far, as those obtained with the electronic camera of Lallemand.

Intensifier screens, consisting of a thin layer of phosphor followed by a thin photocathode, may be used to produce an image-converter of two or more cascaded stages (Morton, Ruedy, Krieger, 1948). When several cascaded stages are used to attain high sensitivity, or to produce high amplification so that short exposure times can be utilized, resolution is seriously impaired. Furthermore, the dark current of an uncooled photocathode will appear as an additional background illumination on the phosphor viewing screen. This places a definite limit on the usefulness of the image-converter tube when photographing faint stars. For good identification, with photographic emulsions normally used in astronomical work, the star should provide at least one-sixth to one-tenth more light to the area it occupies than the background light. The photocathode dark emission of the image-converter tube reduces the effective contrast of the star to the background. Therefore, for large telescopes of great light gathering power and where it can be safely assumed that the flux of light is sufficient to prevent failure of the photographic reciprocity law, if one has all the time needed for conventional photography he will be able to photograph stars as faint or even fainter, without the uncooled image-converter tube than with it, while using the same photographic emulsion. The advantage of the tube is that with it, a shorter exposure time is needed than would be the case with conventional photography. Hence, smaller telescopes may be used without the failure of the photographic reciprocity law making the exposure impossible. Another possibility with the image-converter tube would be to use plates with finer grain than would otherwise be possible, provided the image-converter system has sufficient resolution. The finer grained plates normally require longer exposure times for the same density than the coarser grained plates do, but the finer grained plates show more detail, and also smaller differences in local density variations can be detected. Thus, the gain in the image-converter tube makes it possible to use reasonable exposure times with the finer grained plates. The shorter exposure times may be very important for tracking purposes. Performance beyond the limit of the image-converter tube requires instrumentation of a different type, a type that will provide an increase in contrast and permit a dynamic suppression of the background.

An instrumentation fulfilling the requirements of providing good contrast and permitting suppression of nearly all the background, yet at the same time having exceptionally high sensitivity, was developed by the Aeronautical Research Laboratory of the Wright Air Development Center as a result of several years of research. The best method of providing the required increase in contrast and suppression of the background was found to be that of employing a scanning system (closed circuit television) in which the threshold can be determined arbitrarily by proper biasing of the video amplifier system employed. The pickup tubes available for commercial television are of limited suitability for low light level work because their performance at low light level is restricted by the noise in the scanning beam, which appears as additional fluctuating background. This restriction does not exist in the new intensifier-image-orthicon tube which was developed through this research. The new tube was produced under a research contract with the RCA Laboratories at Princeton, New Jersey, by Dr. G. A. Morton and Dr. J. E. Ruedy. Greatly increased sensitivity is achieved by employing preamplifier stages similar to the cascaded image-converter tube, ahead of the noise-producing scanning section. The scintillations in the dark current of the first photocathode may be observed with such a tube (fig. 1a, 1b), since the constant value of the background that results from the dark current may be suppressed by methods described later.

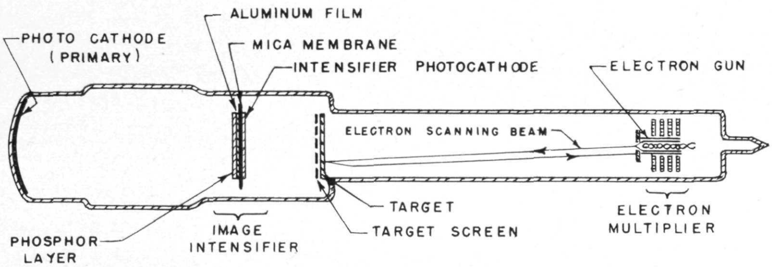


FIGURE 1a. Single stage image optical amplifier tube. **Note:** Aluminum film should read phosphor layer; phosphor layer should read aluminum film.

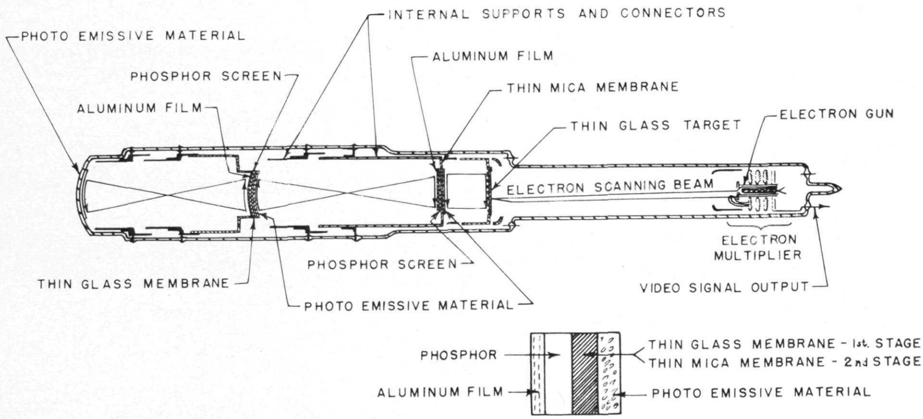


FIGURE 1b. Two stage intensifier image orthicon.

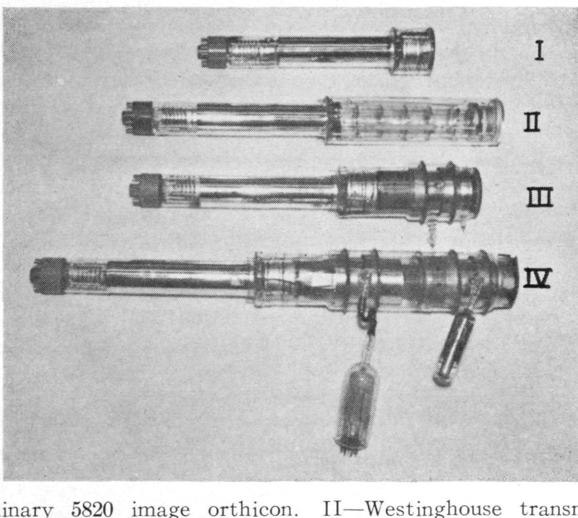


FIGURE 1c. I—Ordinary 5820 image orthicon. II—Westinghouse transmission secondary emission experimental intensifier. III—R.C.A. single stage intensifier orthicon. IV—R.C.A. double stage intensifier orthicon.

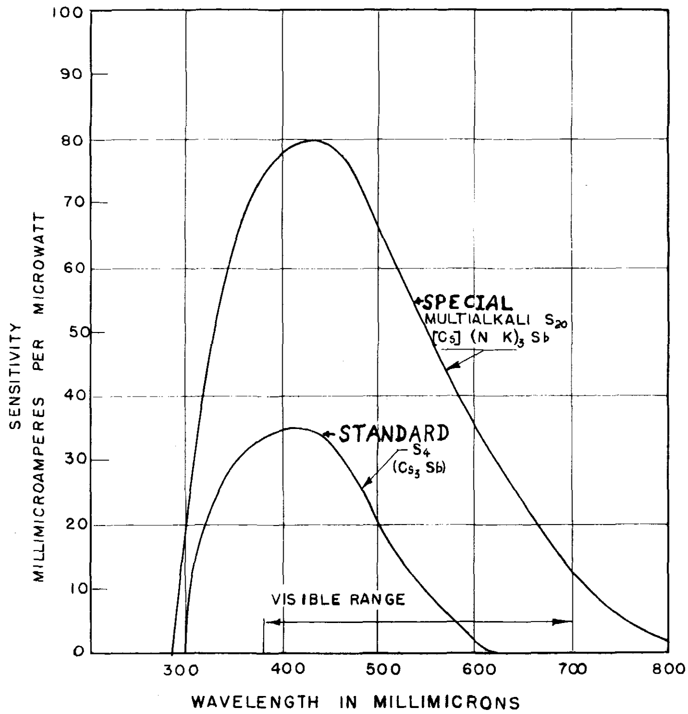


FIGURE 2. Comparative absolute sensitivity of photosurfaces.

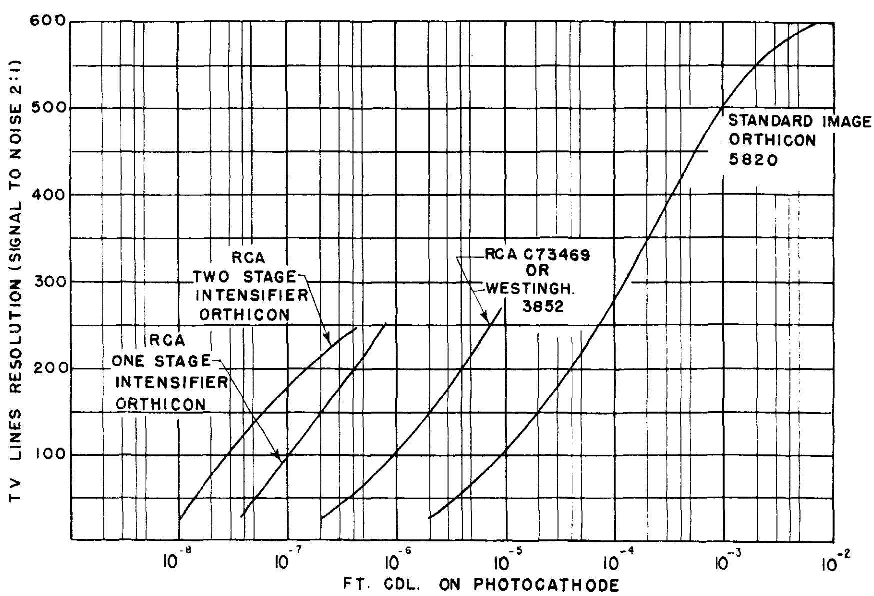


FIGURE 3. Pickup tube performance for exposure time = 1/30 sec.

The photocathodes of the new intensifier-image-orthicon tube have an output as high as 240 μamp per lumen (fig. 2). This is four times the output previously available. These photocathodes have their threshold sensitivity at approximately 8700 Å, which is two thousand angstroms further into the red than that of previously available photocathodes. It is remarkable that the higher yield of these photocathodes and the increased sensitivity to radiation in the near infrared is possible without any significant increase in the dark current. The dark current is each second less than two thousand electrons per square millimeter at 25° C. The intensifier screens that are used consist of a combination of phosphor and photocathode and yield an output of ten to fifteen electrons for each electron that strikes them. Combining the new photocathode and two of the new intensifier screens yields an intensification of the order of one thousand times

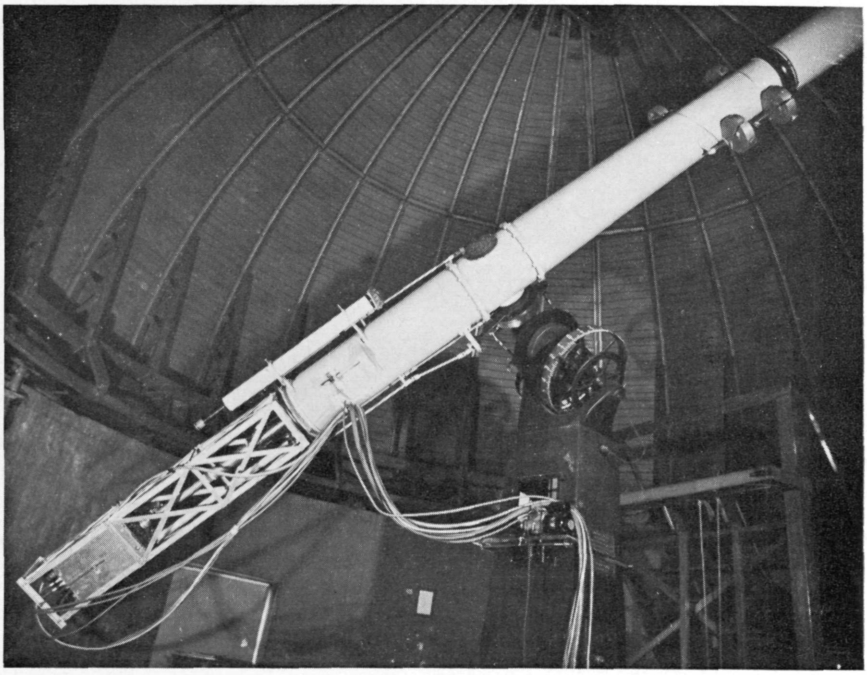


FIGURE 4. Astronomical telescope modified for optical amplification.

(Morton and Ruedy, 1958). It therefore makes possible imaging with about one-thousandth of the light previously required and it becomes a very attractive tube for astronomical work and other low light level observations (Gebel, 1957, 1959).

The desired increase in contrast for star photography can be obtained by direct suppression of a constant "background" from the whole scene by means of the electronic amplifier. The amount of background which can be suppressed is determined by the statistical fluctuations in the background. Theoretically, the ratio of the star signal to these fluctuations can be increased by increasing the length of time utilized in storing the electronic image on the target plate before it is removed by the scanning beam (Gebel and Devol, 1959). Practically, the limits placed on the sensitivity of the equipment and on the enhancement of the contrast lie in the storage capability of the target plate. An effective light flux amplification of 10^9 has been attained in the research and operation is possible at minimum photocathode illumination of approximately 10^{-8} foot-candles. Performance curves for a commercial image orthicon and for two intensifier-image-orthicons are shown in figure 3.

Determination of the capabilities of the equipment and the areas requiring further research was necessary. The equipment was installed on the 10-inch refracting telescope of the Weaver Observatory at Wittenberg University for this purpose and many astronomical observations were taken (Gebel, 1958, 1959; Gebel and Wylie, 1958) (fig. 4, 5). The functions of the essential parts of this

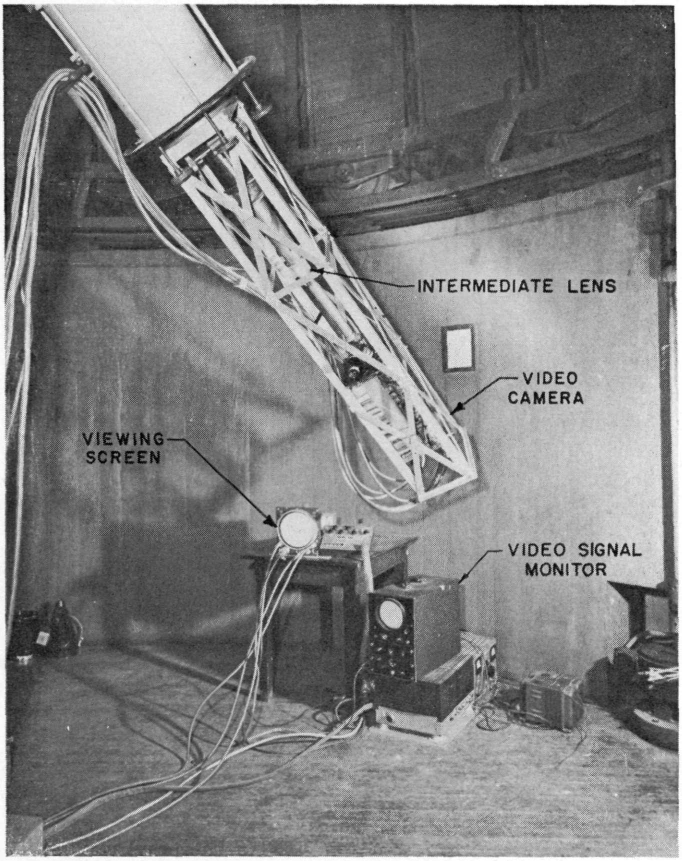


FIGURE 5. Optical amplifying system showing mounting.

type of equipment are identified schematically in the block diagram in figure 6. Modification of the image is electronically accomplished in four stages, as indicated in the diagrams of figure 7, which represent the signal obtained as the scanning beam moves across the target plate. The background noise is illustrated by the waviness in sections *ab* and *cd* of diagram A (fig. 7a). Noise is also present in *ef*, as is indicated by the waviness superimposed on the portion of the signal caused by the celestial body. The upward slope from left to right is the result of a gradual shading in the sky within the field of view.

Two sky shading controls correct the signal from situation A to situation B. One control corrects for the vertical and the other for the horizontal shading variations.

The picture gamma control circuit is an electronic nonlinear device that permits one to increase the contrast. The effect of such an increase is displayed in diagram C, where the upper portion of the signal is accentuated in comparison with the lower portion.

The threshold limiter makes it possible to suppress the lower portion of the signal below a selected level, so that it constitutes that part of the circuitry which weakens or eliminates the background. The result is diagram D (fig. 7b). Finally, the amplitude limiter permits one to limit the upper portion of the signal, thus removing the fluctuations in that portion of the signal caused by the celestial body (diagram E).

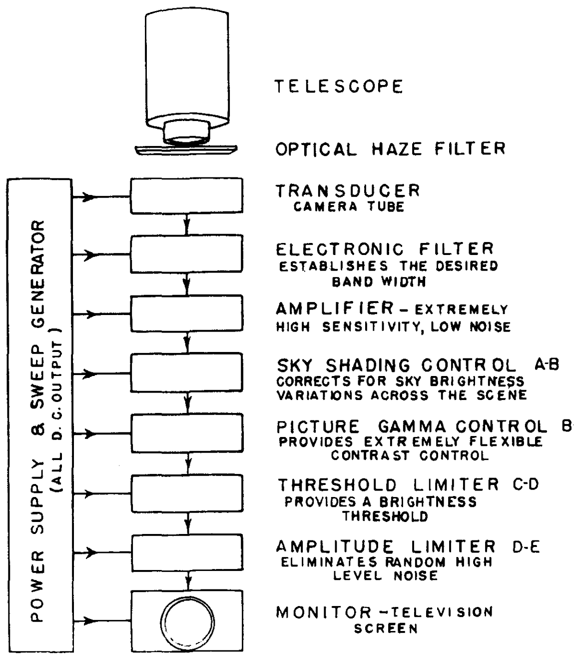


FIGURE 6. Block diagram of telescope and optical amplifier.

The focal length of the telescope was changed from 3.8 m to an equivalent focal length of 15 m by employing an intermediate system. The purpose was to match the resolution of the telescope with the highest resolution of the intensifier-image-orthicon. This is approximately ten optical lines per millimeter at the photocathode (Gebel, 1959). The revised optical system is shown schematically in figure 8.

ASTRONOMICAL PHOTOGRAPHS

Many photographs of celestial bodies were taken for the purpose of exploring the astronomical possibilities of this type of equipment. Unfortunately, the supply of intensifier-image-orthicons is limited at present. Such tubes are hand made, they are very expensive, and they have a short lifetime that averages only

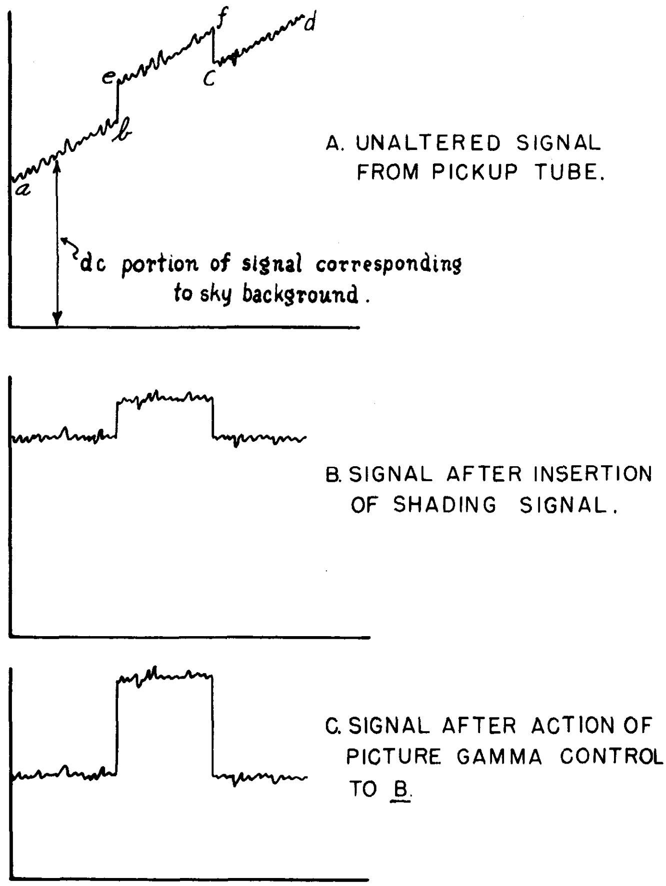


FIGURE 7a. Contrast, background, and noise correction.

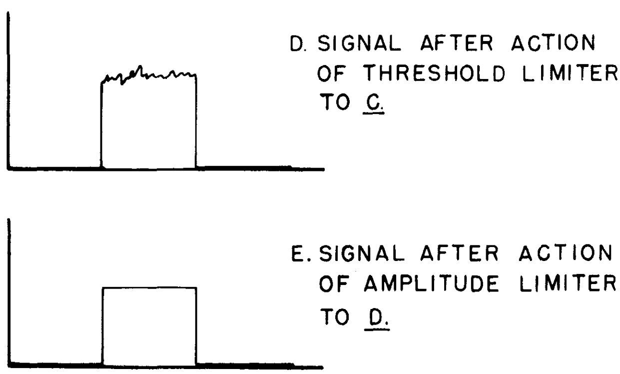


FIGURE 7b. Contrast, background, and noise correction.

about fifty hours. For these reasons another type of pickup tube that was newly designed and specially made (RCA C 73469, Westinghouse 3852) was used in those cases where high sensitivity was not needed. These tubes have a multialkali photocathode, and have improved sensitivity through wide spacing of the target plate meshwire assembly. The performance of these tubes in comparison with conventional tubes may be seen in figure 3. The lifetime of these tubes is several hundred hours since no intensifier is placed ahead of the image section. The cost of this type of tube is much less than the intensifier-image-orthicon tube. Furthermore, the use of the longer-life tube made it possible to test, under all observing conditions, the background suppression and the sky shading capabilities of the specially designed video amplifier.

Figures 9 to 14 are some of the typical pictures taken during daytime hours when the sun was above the horizon. Figures 15 to 18 are typical night time pictures. The explanation of each picture tells which tube was used.

Calculations indicate that with this type of instrumentation and using the Hale telescope of 200-inch aperture, a nighttime exposure of 100 seconds would reach a star of 26th magnitude (Gebel, 1959). The exposure time in the photographs shown here was a twenty-fifth of a second but a shorter time would have been sufficient in a great many cases. The large size of the star images in the photographs is due to the bad seeing that is characteristic of daytime observations. The bad seeing is a rapid fluctuation in the star's brightness accompanied by small

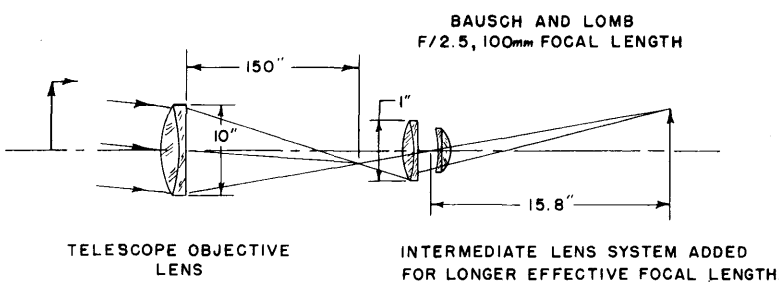
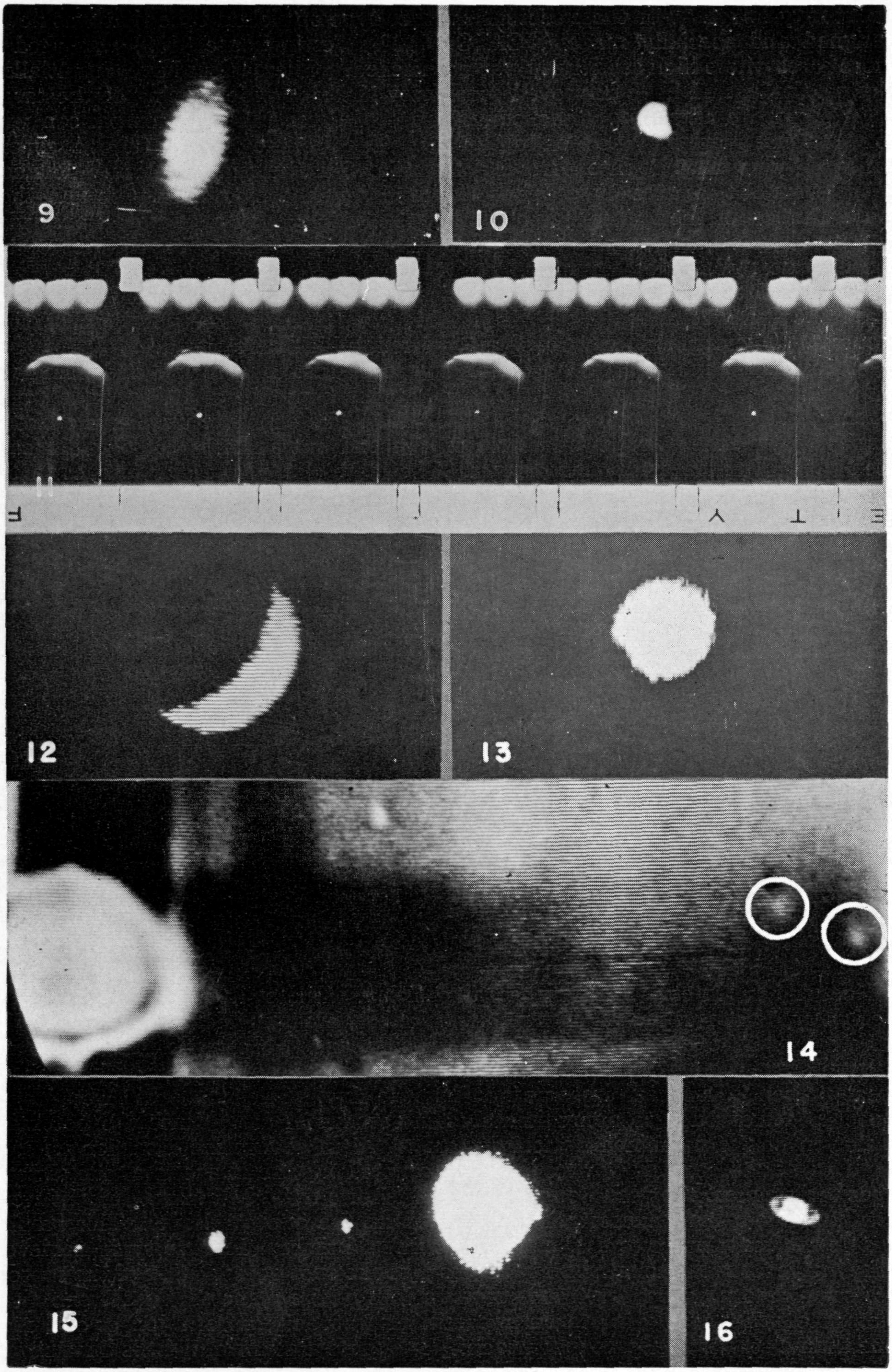


FIGURE 8. Optical system.

and equally rapid changes in apparent position. These jitters are produced by the dynamic changes in the different layers of air through which the beam of light passes. Springfield, Ohio, is an industrial city, and in Springfield it is unusual to have seeing better than three to five seconds of arc at night, and as much as twenty seconds has been observed during the day. The image of Arcturus in figure 10 corresponds to approximately ten seconds of arc. Since the potential resolution of the combined optical system at 15 m equivalent focal length was found to be 2.5 seconds of arc, the area covered by the image is about sixteen times the smallest that can be resolved. It follows that the quanta of light were distributed over an unnecessarily large area on the photocathode. This results in a lower contrast toward the background. Optimum detectivity is achieved if the image from the celestial body covers just one spot of resolution of the sensor. The same reasoning applies to the observations of the planets. In astronomical photography a planet of a certain apparent magnitude requires a longer exposure time than a star of the same magnitude. The same amount of light is distributed over a larger area, since the planet is not a point source (Gebel, 1959).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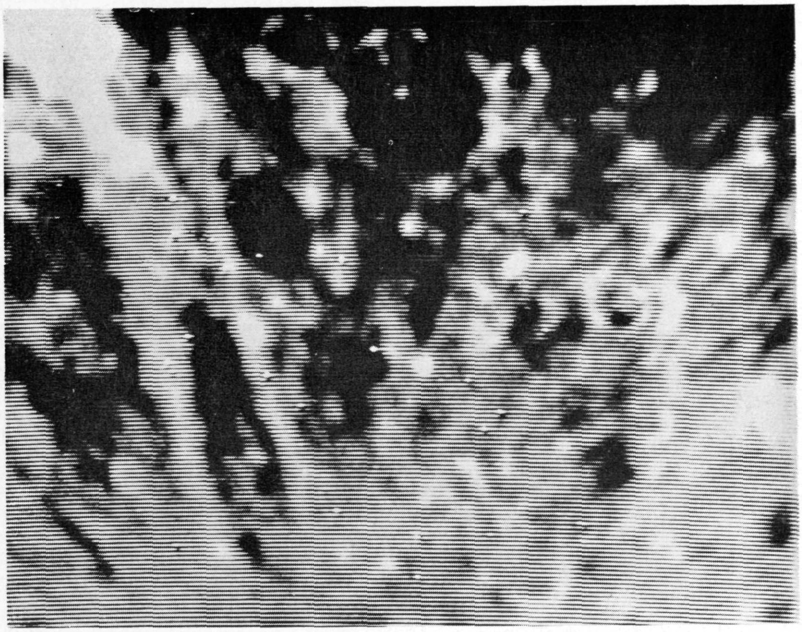

FIGURE 17a. Night shot of moon, area of Crater Tycho, at 23:30 EST, August 27, 1958. Westinghouse tube type 3852. 15 meter focal length.

A conclusion from the foregoing is that, in order to achieve optimum conditions for photographing point sources, one should adjust the focal length to match the seeing conditions so that all quanta of light are concentrated on one point of resolution.

Figure 11 displays a few frames of a midafternoon motion picture of the star Vega. The frames show the jitters caused by the bad seeing conditions. The picture of Venus (fig. 12) was taken at 2:00 PM on January 9, 1958. It was taken

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EXPLANATION OF FIGURES IN PLATE

9. Saturn at 19:25 EST, July 24, 1957. Sunset was 19:57 EST, elevation of Saturn was 26° and angle between it and sun was 125°. Cat. Mag. was 0.5, RCA tube type C73469. Film exposure time was 1/25 sec.
10. Arcturus at 15:20 EST, August 6, 1957. Sunset was 19:43 EST, elevation of Arcturus was 53° and angle between it and sun was 73°. Cat. Mag. was 0.2, RCA tube type C73469. Film exposure time was 1/25 sec.
11. Vega at 14:00 EST, September 11, 1957. Sunset was 18:50 EST, elevation of Vega was 25.6° and angle between it and sun was 102°. Cat. Mag. was 0.1, RCA tube type C73469. Film frame rate was 24 per sec.
12. Venus at 14:00 EST, January 9, 1958. Sunset was 17:28 EST, elevation of Venus was 35° and angle between it and sun was 28°. Cat. Mag. was −4.2, RCA single stage intensifier tube. Film exposure time was 1/25 sec.
13. Jupiter at 08:16 EST, January 19, 1958. Sunrise was 07:54 EST, elevation of Jupiter was 32° and angle between it and sun was 88°. Cat. Mag. was −1.6, RCA tube type C73469. Film exposure time was 1/25 sec.
14. Jupiter and satellites 1 and 2 at 07:37 EST, February 9, 1958. Sunrise was 07:36 EST, elevation of Jupiter was 31° and angle between it and sun was 108°. Cat. Mag. of satellites was 5 and 6, RCA tube type C73469. Film exposure time was 1/25 sec.
15. Night picture of Jupiter and Galilean satellites at 20:30 EST, May 12, 1958. Cat. Mag. of satellites was 5 and 6. Westinghouse tube type 3852. Film exposure time was 1/25 sec.
16. Night picture of Saturn at 21:10 EST, August 27, 1958. RCA single intensifier tube. Film exposure time was 1/25 sec.

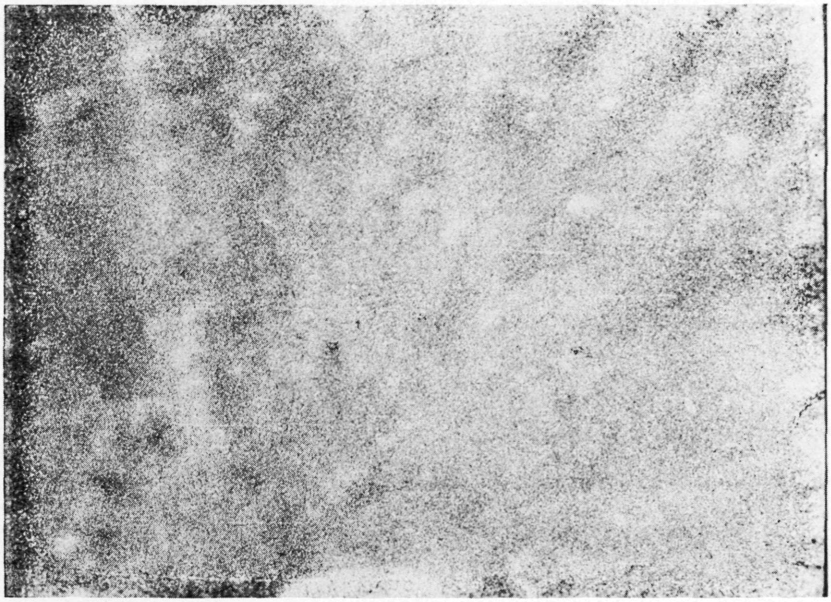

FIGURE 17b. Night shot of moon, area of Crater Tycho, at 23:35 EST, August 27, 1958. Convential photographic methods using 35mm Tri-X film; 15 meter focal length.

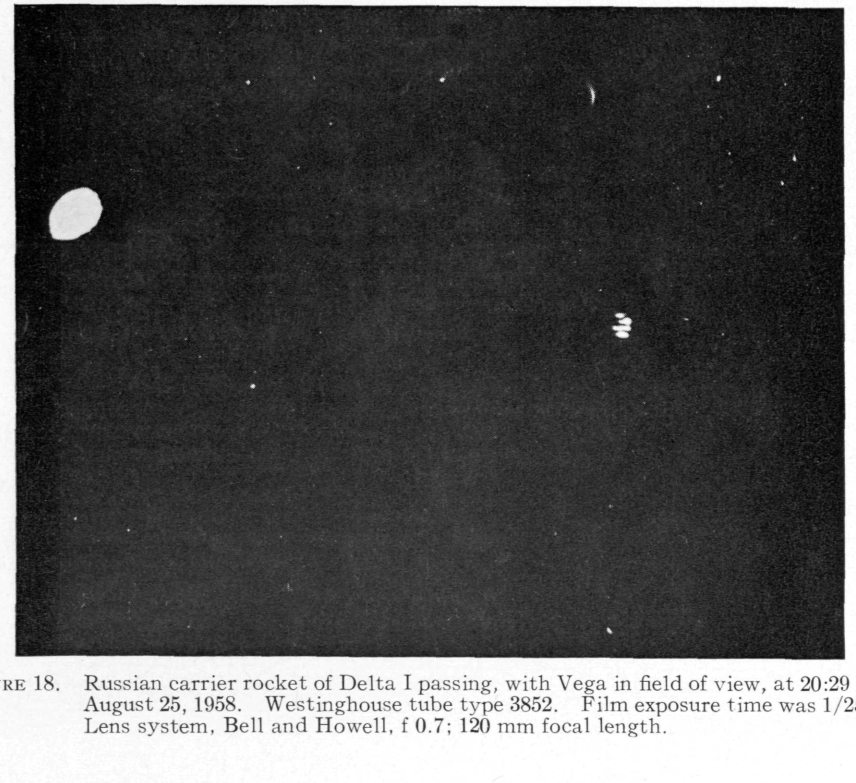

FIGURE 18. Russian carrier rocket of Delta I passing, with Vega in field of view, at 20:29 EST, August 25, 1958. Westinghouse tube type 3852. Film exposure time was 1/25 sec. Lens system, Bell and Howell, f 0.7; 120 mm focal length.

with a single stage intensifier-image-orthicon tube. The distinct horizontal lines in the picture are the scan lines. The angular diameter of Venus was 53 seconds of arc at the time. Venus is reproduced by 39 lines, which means that each line represents 1.3 seconds of resolution. The fluctuations caused by the scintillations of the air were a multiple of this value, so the air scintillations represent the true limiting value of the resolution for this observation. Since the proper choice of the equivalent focal length permits a matching of the fluctuations to the resolution of the pickup tube and the scanning lines, one can always adjust the system so that the seeing conditions determine the limit in resolution.

The work at Wittenberg University was undertaken to show the potentialities of a system of optical amplification for astronomical observations using the principles of closed circuit television. The remarkable ability to control contrast and to suppress the background makes this system useful also for artificial satellite observation and tracking during the daytime hours. It is useful for aerial reconnaissance and for many other purposes. In space exploration the advantage of this kind of optical amplification is obvious because the pictures can easily be transmitted over cosmic distances.

SUMMARY

The advantages of observing and photographing celestial bodies with a light amplifier that employs the closed circuit television principle are explored and treated here. Special pickup tubes were developed to insure optimum performance. The electrical signals from the pickup tube are electronically amplified and modified. The image is reproduced by a cathode ray tube and photographs may be obtained from the screen of this tube.

The electronic amplification of the electrical signal permits light intensification of 10^9 times. The modification of the signal makes almost complete suppression of the background possible. It permits astronomical observations during the day and also at night that are not possible with systems in which the background cannot be suppressed. Photographs of celestial bodies taken at the Weaver Observatory of Wittenberg University are shown here.

ACKNOWLEDGMENT

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